Radio Wave Propagation for Communication on and around Mars

Highlights of Part I: Propagation Through Mars Environment

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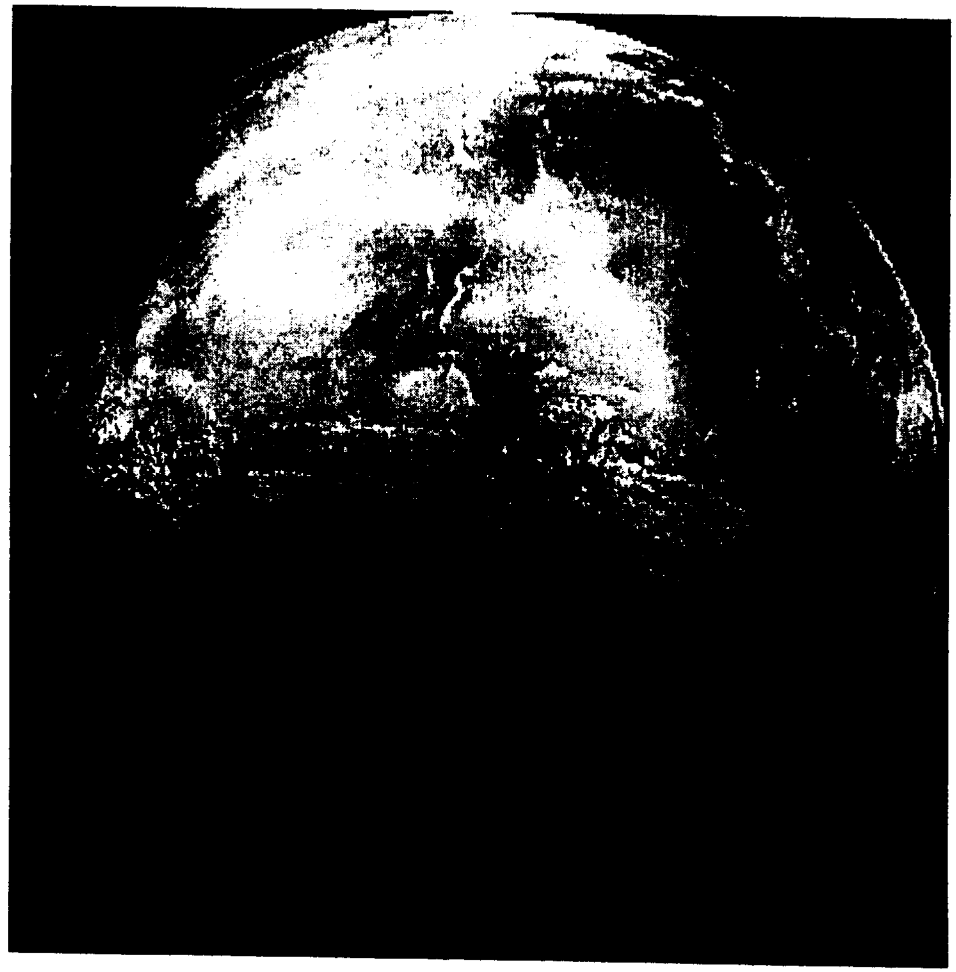
Part I: Propagation Through Mars Environment

Highlights of Part I: Radio Wave Propagation Through Mars Environment

- Study of effects of Martian environment on radio wave propagation
- Review of all Mars measurements and analysis related to wave propagation
- Update of knowledge about mars with the latest measurements of MGS
- Collection of the basic information of Mars environment parameters
- Theoretical treatment of wave propagation from Mars surface into the space

- Original research done using the latest available data
- Recommendations presented for future NASA Mars Missions
- Extension of wave propagation knowledge to a planet other than earth
- Extensive literature search through all Mars publications

Mars and Its Surface Structure



Source: NASA

Table 1-1. Mars Statistical Facts

Diameter	6,785 km (4,217 miles)
Length of Day	24 hrs 37 min
Mass	0.11 x Earth
Length of year	687 Earth days
Density	3.9 (water=1)
Tilt of Axis	25° 12"
Minimum Distance from Sun	205 million km (128 million miles)
Maximum Distance from Sun	249 million km (155 million miles)
Surface Gravity	0.38 x Earth
Temperature	-82° C to 0° C (-116° F to 32° F)
Minimum Distance from Earth	55 million km
Maximum Distance from Earth	~400 million km
Satellites	Deimos (8km) and Phobos (28x20 km)

Table 1-2. Mars Exploring Missions

Mariner 4, 6, 7, & 9	1964, 1969, 1971
Russian Mars 2 & 3	1971 & 1972
Russian Mars 4, 5 & 6	1974
Viking I & II	1975
Russian Phobos	1989
Mars Observer	1993
Mars Pathfinder	1997
Mars Global Surveyor	1998
Mars '98 (Climate Orbiter & Polar Lander)	1999
Planet - B (Japan)	1999
Mars 2001 (Lander & Orbiter)	2001
Mars 2003 (Lander and Rover)	2003
Mars 2005 (Sample Return)	2005
Mars Human Exploration Program	2010

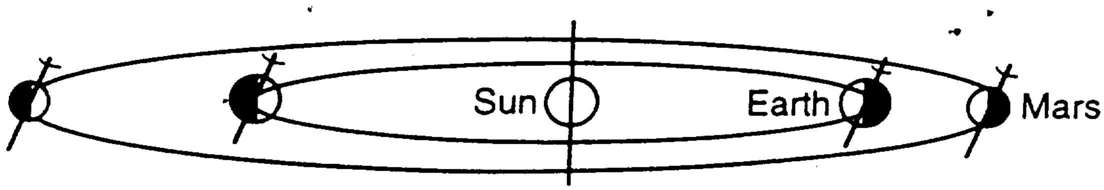
Mars Orbit

The Martian climate and surface features are significantly influenced by the shape of the Martian orbit. The eccentricity of Mars orbit is 0.093, in contrast to the near-circular earth orbit (0.017). The high eccentricity affects the Mars in a number of ways.

When Mars is at its perihelion (closest point to the sun), it happens that the southern Martian hemisphere tilts toward to the sun. Thus the southern hemisphere has a hot and short summer.

When Mars is at its aphelion, because northern Martian hemisphere tilts toward to the sun, northern hemisphere has a clod and long winter.

These differences have generated profound effects on Martian atmospheric circulation patterns, surface geomorphologic change, duststorm and polar ice cap formation, etc.



Fundamental Theory For Radio Wave Propagation

For the low frequency waves, the refractive index of a medium containing free electrons, with a superimposed steady magnetic field, is given by the Appletion-Hartree formula.

$$n^2 = 1 - \frac{X}{1 - iZ - \frac{Y_T^2/2}{1 - X - iZ} \pm \sqrt{\frac{Y_T^4/4}{(1 - X - iZ)^2 + Y_L^2}}} \qquad (1\text{-}1)$$

Thus refractive index is mainly the function of electron density, background magnetic field.

For the high frequency waves (> 1 GHz), the radiometeorology has some effects on the wave propagation. These effects mainly take place in the lower atmospheric portion: the troposphere.

$$N = (n-1) \times 10^6 \text{ (N unit)} \qquad (1\text{-}2)$$

$$N = 77.6\frac{P}{T} + 3.73 \times 10^5 \frac{P_{wv}}{T^2} \qquad (1\text{-}3)$$

Thus, the tropospheric radio refractivity is a function of atmospheric pressure, P (mb), absolute temperature, T (K), and water vapor pressure, P_{wv} (mb).

Martian Dayside Ionosphere and Surface Magnetic Anomalies

Source: NASA

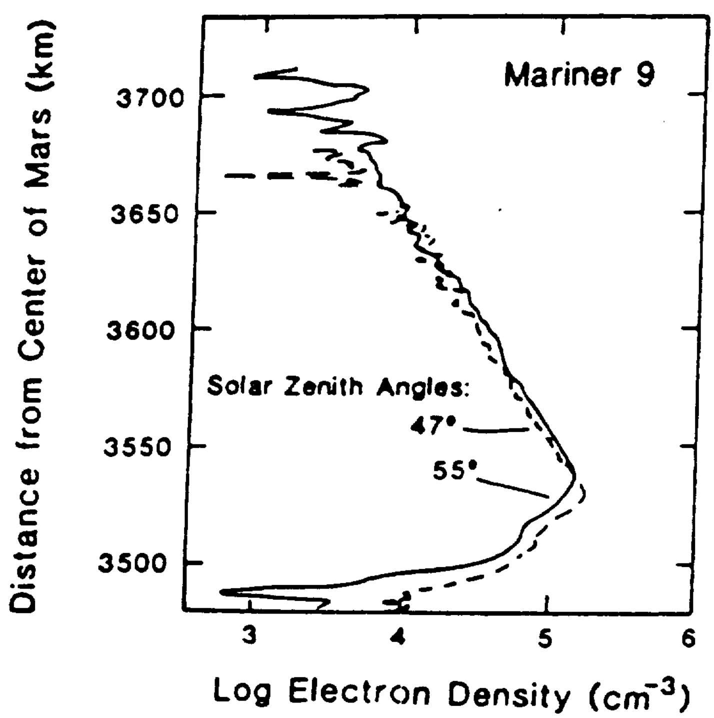
Martian Ionospheric Model

The Martian dayside ionosphere of Mars is generated through the photo-ionization of its upper atmosphere. The top height of ionosphere (ionopause) is dependent on solar wind pressure. A comet-like structure with low electron desity can extends several thousand kilometers at nightside. The dayside Martian ionosphere may be described using a simple Chapman layer model. Martian dayside ionosphere has stable peak height and peak density. Its peak height is between 120 and 130 km.

$$N(h) = N_m \exp\{0.5[1-(h-h_m)/H - \exp(-(h-h_m)/H)]\} \qquad (2\text{-}1)$$

where
$$N_m = N_0(\cos\chi)^k \qquad (2\text{-}2)$$

and
$$h_m = h_0 + H \ln \sec\chi \qquad (2\text{-}3)$$



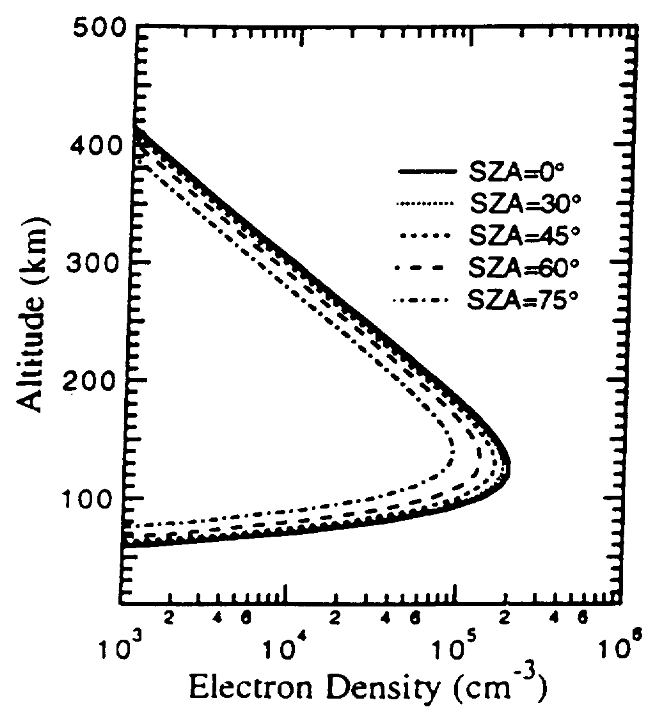


Table 2-1. Martian Ionospheric Peak Electron Densities and Critical Frequencies

Ionos pheric Cond ition		Mars			Earth	
		$n_0\,(m^{-3})$	$n_0\,(cm^{-3})$	$f_0\,(MHz)$	$n_0\,(cm^{-3})$	$f_0\,(MHz)$
Dayside	Solar Max.	2.5×10^{11}	2.5×10^{5}	4.5	2.0×0^{6}	12.7
	Solar Min.	1.0×10^{11}	1.0×10^{5}	2.9	5.0×10^{5}	6.3
Nightside	Solar Min.	5.0×10^{9}	5.0×10^{3}	0.6	2.0×10^{5}	4.0
Dayside	TEC	$2.0 \times 10^{16}\,m^{-2}$	$2.0 \times 10^{12}\,cm^{-2}$			

* There is no nightside ionospheric data available during solar maximum

Table 2-2. Usable Critical Frequencies and Hop Distances for various Launch Angles

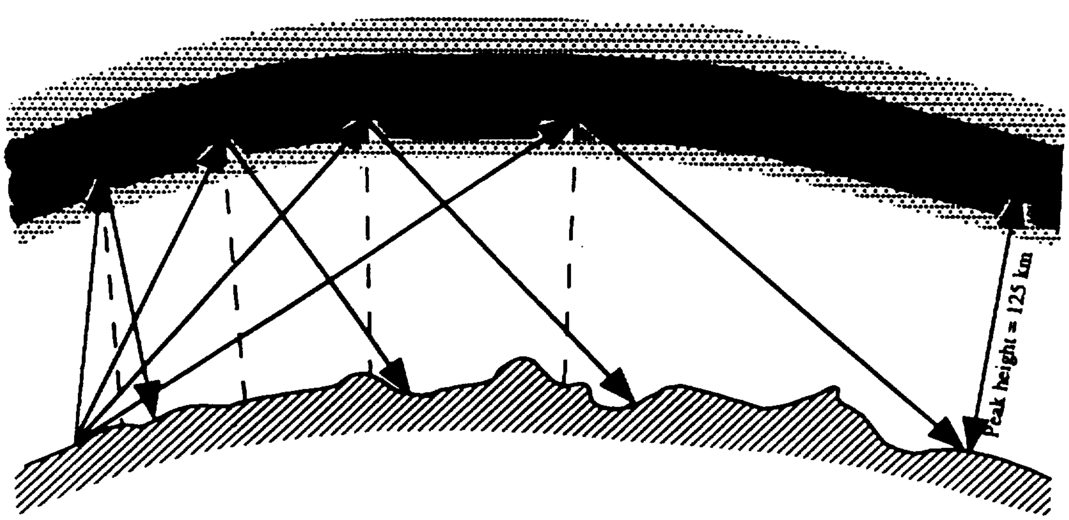
Launch Angle θ_0	0°	15°	30°	45°	60°	75°
Maximum Usable Frequency (MHz)	4.0	4.14	4.62	5.66	8.0	15.5
One Hop Distance (km)	0	67.0	144.3	250.0	433.0	933.0

Table 2-3. Effects of Total Electron Contents ($TEC=2 \times 10^{16}/m^2$) of the Mars Ionosphere on Wave Characters (one-way path)

	100 MHz	500 MHz	1 GHz	5 GHz	10 GHz
Faraday Rotation $\phi=(2.36 \times 10^4/f^2)B_L\,TEC$	500"	20"	5"	0.2"	0.05"
Range Delay $\Delta R=(40.3/f^2)TEC$	80 m	3.3 m	0.8 m	0.032 m	0.008 m
Phase Advance $\Delta\phi=(8.44 \times 10^7/f)TEC$	169 rad	34 rad	16.9 rad	3.4 rad	1.69 rad
Time Delay $\Delta t=(1.34 \times 10^7/f^2)TEC$	270 ns	10.8 ns	2.7 ns	0.108 ns	0.027 ns

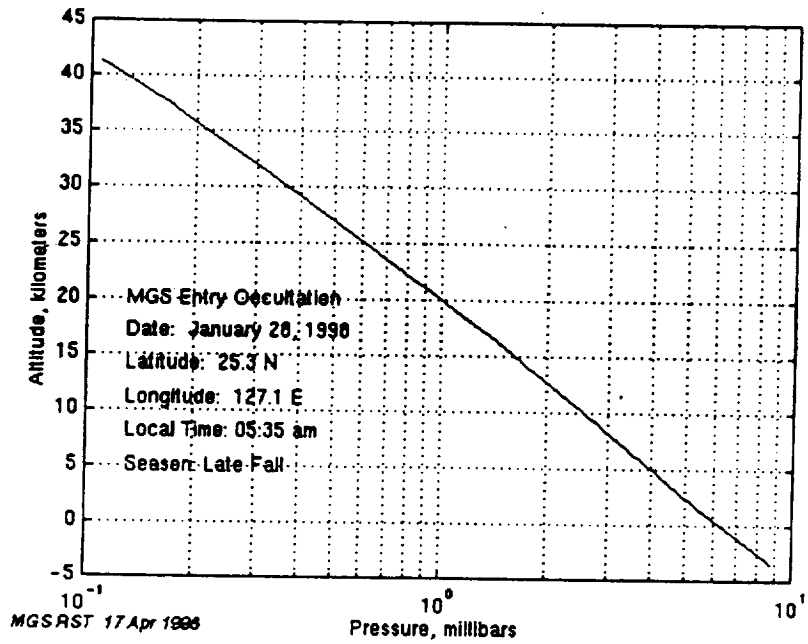
Recommendation:

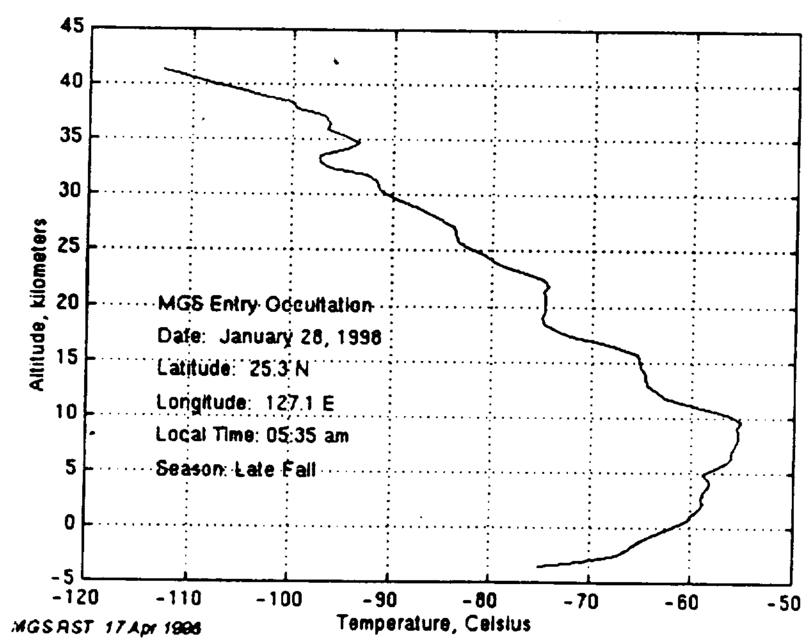
The Martian ionosphere may play an important role in the future Mars ground to ground communication. The Martian ionospheric critical frequency is ~ 4.0 MHz for vertical incident. The frequency is high enough to carry the information. The stable condition in the dayside ionosphere is favor to oblique incident communication using the ionosphere as a reflector from Martian surface to surface. Using Mars ionosphere can also perform trans-horizon (or beyond line of sight) communication for the future Martian colonies, rover, vehicles and robots released from Mars landers. However, because of low usable frequency and very unstable condition, the nightside ionosphere has some limitations using for global communication.

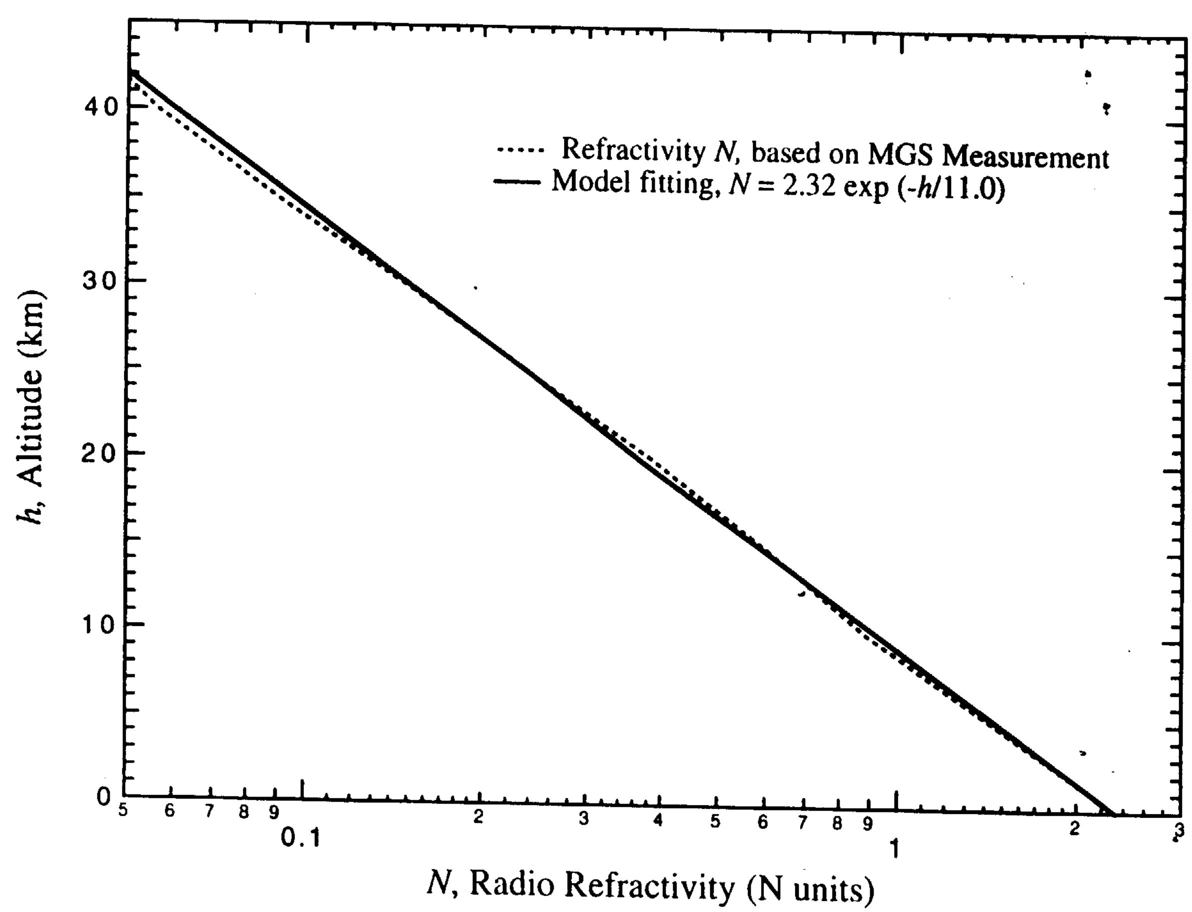


Mars Atmosphere and Its Effects on Propagation

Martian Tropospheric Structure:

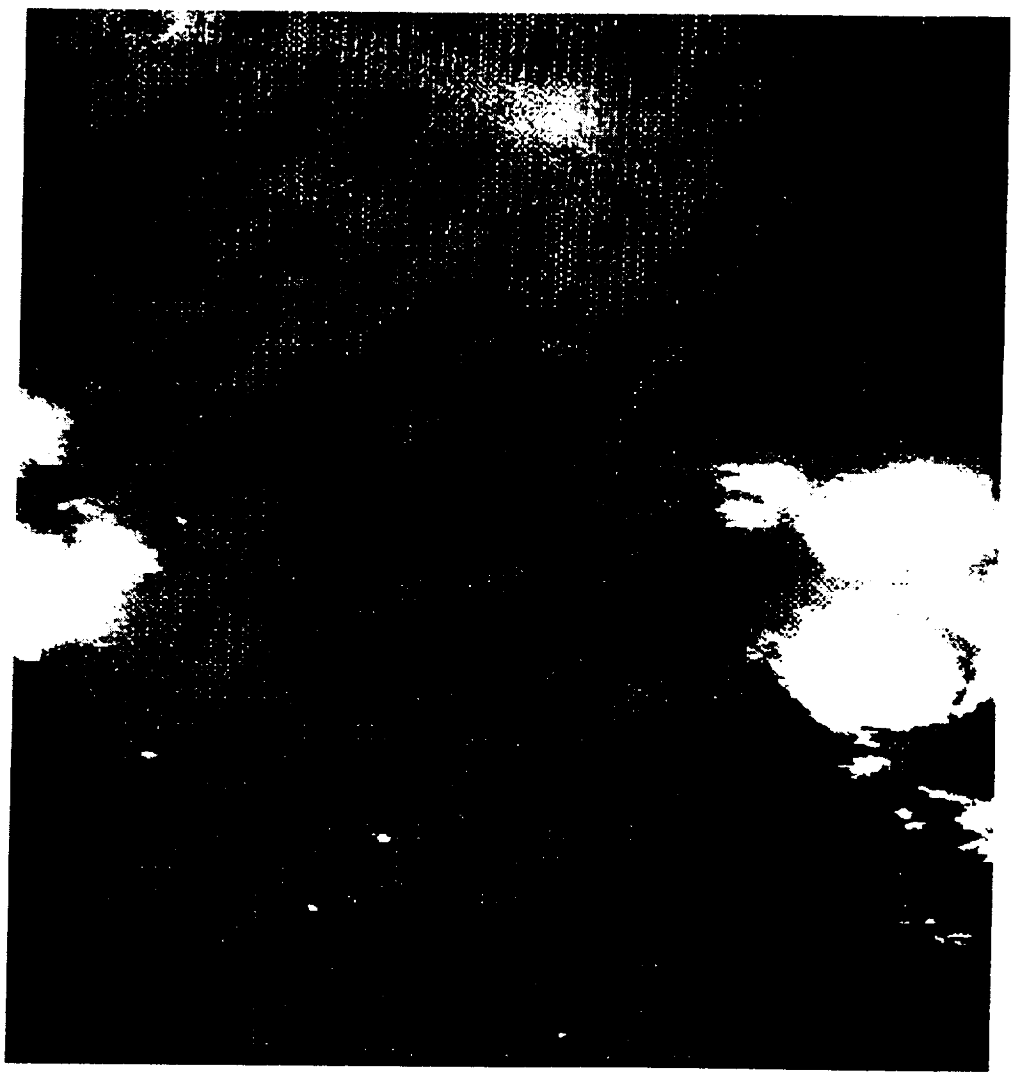






Refractivity N, based on MGS Measurement
Model fitting, N = 2.32 exp (-h/11.0)
h, Altitude (km)
0
10
20
30
40
5
6
7
8
9
0.1
2
3
4
5
6
7
8
9
1
2
3
N, Radio Refractivity (N units)

Martian Clouds and Its Weather System



Source: NASA

Table 4-1. Surface atmospheric parameters at Mars and Earth

Planets	P, pressure (mb)	T, temperature (°K)	M, mean molecule weight	ρ, mass density (kg/m^3)	N, number density (m^{-3})	V_m, mole volume (m^3/kmole)	H, scale height (km)
Mars	6.1	210	43.34 g/mole	0.021	2.85×10^{23}	2.1×10^3	~11.1
Earth	1013	300	28.61 g/mole	1.29	2.7×10^{25}	22	~9.5

Table 4-2. A comparison of top six atmospheric compositions on Mars and Earth ground

Gaseous Composition		Mars Surface (6.1mb, 210°K)				Earth Surface (1013mb ,300°K)			
molecules	M_i, weight (g/mole)	γ_i, mix ratio (by volume)	β_i, fraction in weight	ρ_i, mass density (g/m^3)	n_i, number density (cm^{-3})	γ_i, mix ratio (by volume)	β_i, fraction in weight	ρ_i, mass density (g/m^3)	n_i, number density (cm^{-3})
CO_2	44.02	95.32%	96.77%	20.32	2.8×10^{17}	400ppm	615ppm	0.8	1.1×10^{16}
N_2	28.02	2.7%	1.74%	0.365	7.8×10^{15}	78.09%	76.5%	986.9	2.1×10^{19}
A_r	39.96	1.6%	1.48%	0.311	4.7×10^{15}	0.93%	1.3%	16.8	2.6×10^{17}
O_2	30.00	0.13%	900ppm	0.02	3.8×10^{14}	20.95%	21.97%	283.7	5.7×10^{18}
CO	28.00	800ppm	517ppm	0.011	2.3×10^{14}	0.2 ppm	0.2ppm	2.6×10^{-4}	5.6×10^{12}
H_2O	18.02	300ppm	125ppm	0.0026	8.8×10^{13}	1.0%	0.63%	8.1	2.7×10^{17}

* ppm: part per million.

Table 4-3. Ratios of atmospheric compositions between Earth and Mars

Ratios (earth/Mars)	CO_2	N_2	A_r	O_2	CO	H_2O
for γ_i (fraction by volume)	4.2×10^{-4}	28.9	0.58	**161**	2.4×10^{-4}	**33.3**
for β_i (fraction by weight)	6.4×10^{-4}	44	0.88	244	3.9×10^{-4}	50.4
for ρ_i and n_i (density)	0.04	2704	54	1.4×10^4	0.024	3068

Table 3.4. Optical Depths of Clouds and Fogs at Earth and Mars

Atmospheric Condition	Earth		Mars	
	Optical Depth	Distribution	Optical Depth	Distribution
Clouds H_2O	~5	50% coverage	~1.0	Winter polar; behind mountains
Clouds CO_2	None	None	~0.001 ~1.0	Many places Winter polar
Fog	~3	Many places	~0.2 ~1.0	Morning Valleys & crater bottoms
Aerosol Dust	To be provided	To be provided	0.5	Everywhere
Dust Storms	To be provided	To be provided	10.0	Southern hemisphere, or global

Surface Atmospheric Composition and Gaseous Attenuation

Surface Pressure: ~6.1 mb (variable)

Surface Density: ~0.020 kg/m^3

Scale height: ~11.1 km

Average temperature: ~210 K

Diurnal temperature range: 184 K to 242 K

Mean molecular weight: 43.34 g/mole

Atmospheric composition (by volume):

Major: Carbon Dioxide (CO2) - 95.32% ; Nitrogen (N2) - 2.7%
Argon (Ar) - 1.6%; Oxygen (O2) - 0.13%; Carbon Monoxide (CO) - 0.08%

Minor (ppm): Water vapor (H2O) - ~150-300 (variable);
Nitrogen Oxide (NO) - 100; Neon (Ne) - 2.5;
Hydrogen-Deuterium-Oxygen (HDO) - 0.85; Krypton (Kr) - 0.3;
Xenon (Xe) - 0.08, Ozone (O_3) - 0.04 - 0.2.

Gas Thermal Dynamic Equations

$$p_i = n_i k_B T, \quad P = N k_B T, \quad P = \sum_i p_i$$

$$\gamma_i = \frac{p_i}{P} = \frac{n_i}{N}, \quad N = \sum_i n_i$$

$$\beta_i = \frac{\rho_i}{\rho} = \frac{\gamma_i M_i}{M}, \quad M = \sum_i \gamma_i M_i,$$

$$\rho_i = \frac{n_i M_i}{N_A} = \frac{\gamma_i M_i \rho}{M} = \beta_i \rho, \quad \rho = \frac{NM}{N_A}, \quad \rho = \sum_i \rho_i$$

$$n_i = \frac{p_i}{k_B T} = \frac{\gamma_i \rho N_A}{M} = \frac{\rho_i N_A}{M_i}, \quad V_m = \frac{N_A}{\sum_i n_i}$$

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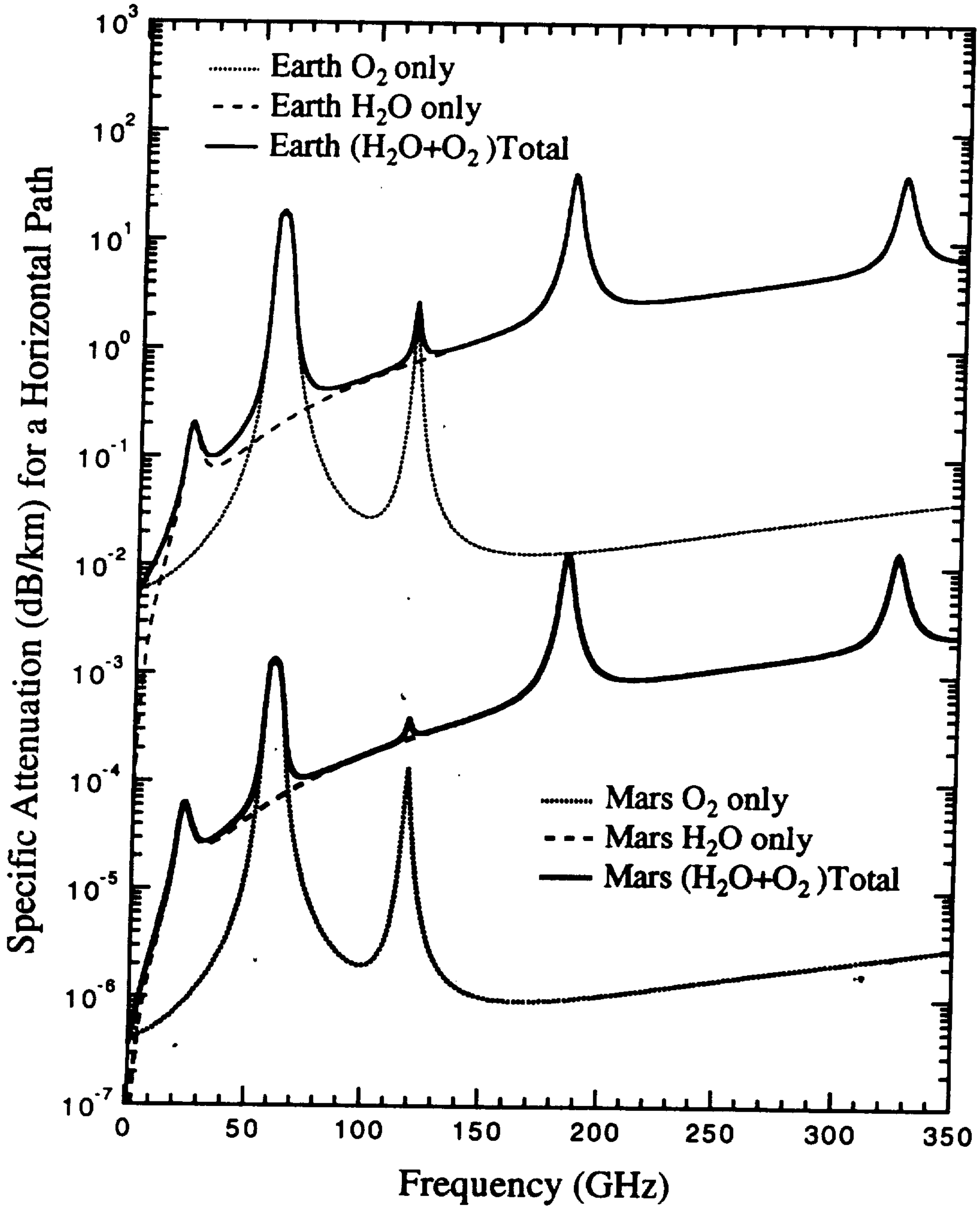
Atmospheric Absorption Attenuation by Wator vapor and Oxygen at Earth and Mars Surface



Martian Dust Storms and Its Effects on Propagation

On Mars the threshold velocities are much larger than those on earth because of the thinner atmosphere, but depending the surface pressure. The optimum size for particle movement on Mars is near 0.1 mm, close to the size for earth. Threshold shear velocities (V_t) required to move the 0.1-mm particles range from 1.4 m/sec. On earth threshold velocities at the optimum size are close to 0.2 m/sec.

Table 5-1. Martian Great Dust Storms

Year	Observation	L_s	Initial Location
1909 (Aug)	Earth		
1911 (Nov)	Earth		
1922	Earth	192	
1924 (Oct)	Earth		
1924 (Dec)	Earth	237	Isidis Planita
1939	Earth		Utopia
1941 (Nov)	Earth		South of Isidis
1943	Earth	310	Isidis
1956	Earth	250	Hellespontus
1958	Earth	310	Isidis
1971 (July)	Earth	213	Hellespontus
1971 (Sept)	Earth, Mariner 9	260	Hellespontus
1973	Earth	300	Solis Planum
1977 (Feb)	Viking	205	Thaumasia
1977 (June)	Viking	275	
1979	Viking	225	

A Martian Dust Storm Observed by Viking Orbiter in 1977 Midsouthern Spring

Source: NASA

A Martian Dust Storm Near the South Polar Region

Source: NASA

Martian dust storm types include: planet-encircling - those dust storms which are believed to have encircled the planet at some latitude; regional dust storms, clouds and hazes with a spatial dimension > 2000 km; local dust storms, clouds and hazes with a spatial dimension < 2000 km.

Mars dust basically consists of basalt and montmorillonitic clay. Clear atmosphere corresponds to a background aerosol of optical depth 0.3 – 0.5 at a wavelength of 0.67mm, while during the most intense portions of the global storms the opacity was found to increase to 4.0 – 5.0. A local storm generally has a spatial extent of several hundreds of kilimeters. A great dust storm can have a size as big as the state of Texas, even covers half planet.

Dust size distribution have been modeled using a modified gamma function [Toon et al., 1977; Hunt, 1979]:

$$N(r) = cr^{\alpha} . \exp[-(\alpha/\gamma)(r/r_m)^{\gamma}] \quad (5\text{-}2)$$

Chu [1979] and Goldhirsh [1982] have summarized the studies of the effects on radio wave propagation due to earth dust storms. Microwave attenuation $A(\lambda)$ is

$$A(\lambda) = \frac{189r}{\lambda V}\left[\frac{3\varepsilon''}{(\varepsilon'+2)^2 + \varepsilon''^2}\right] \quad (5\text{-}3)$$

Smith and Flock [1986] have performed a first study of X and Ka band wave propagation through Martian dust. Attenuation may be expressed as

$$A(\lambda) = 54.62 \frac{r\tau}{\lambda} \left[\frac{3\varepsilon''}{(\varepsilon' + 2)^2 + \varepsilon''^2} \right] \qquad (5\text{-}4)$$

When a distribution of particle size is available, we can use another type of expression as [Goldhirsh, 1982]:

$$A(\lambda) = \frac{1.029 \times 10^6 \varepsilon''}{\lambda[(\varepsilon' + 2)^2 + \varepsilon''^2]} \sum_i N_i r_i^3 \qquad (5\text{-}5)$$

Table 5-2. Dielectric Permittivity Index of Dust Particles

Index ε	10 GHz Ghobrial (1980)	10 GHz Clay	10 GHz Sand	S band Goldhirsh (1982)	32 GHz Clay*	8.8 GHz Clay*	Dust at 20μm*	Dust at 2 μm*
ε'	4.56 (+0.11, -0.24)	7.42 (+1.73, -1.22)	3.35 (±0.03)	4.56	2.5	2.5	2.0	3.0
ε''	2.51 (+0.074, -0.066)	1.119 (+0.597, -0.437)	0.042 (±0.02)	0.251	0.06	0.02	0.4	0.1

* Smith and Flock [1986]

Table 5-3. A Comparison of Dust Storm Parameters betwen Earth and Mars

	N_T m^{-3}	ρ g/m^3	Mean Size (μm)	Maximum Size (μm)	Visibility (m)	Path Length	Attenuation, at 32 GHz	Mass Loading
Earth	10^8	2.6×10^6	30-40	80-300	5.1-3.8	10km	65 dB	40-60 g/m^3
Mars	3×10^7	3.0×10^6	1-10	20	184	10km	3 dB	0.4 g/m^3

Summary

We recommend to use the dayside Martian ionosphere as a reflector for global communication, because the dayside ionosphere has stable density peak and usable critic frequncy. This is very crucial for the future Mars ground to ground communication. The dayside ionosphere has been well modeled as a Chapman layer. We suggest to perform the Martian nightside ionospheric modeling study. Because the nightside ionosphere has very little measurements available, we propose to drop a digital ionosond instrument into the Mars surface for data collection.

Even though the Martian tropospheric radio refractivity has small value, it still can cause the ray bending and multipath effects. We recommend to perform an accurate calculation on excess phase and group delays (range and time delays). Other effects, such as range rate errors, appearance angle deviation, defocusing loss on Mars, etc. are also needed to be estimated. Ice depolarization effects due to Martian clouds on radio waves is unknown yet, which is expected to be small, because lower optical depth and thinner layer of cloud.

Total Martian atmospheric gaseous attenuation is expected to be less than 1 dB on microwaves band, because the Martian atmosphere has very low concentration in uncondensed H_2O and O_2. An accurate calculation for

zenith opacity requires the information about scale heights of H_2O and O_2 distribution. An accurate water vapor altitude profile at Mars is not available yet. Under the normal condition, CO_2 and N_2 gases do not have electric or magnetic dipoles and do not absorb electromagnetic energy from the waves. However, they may generate the dipoles through a collision and interact with waves under a high density condition and absorb electromagnetic waves in the infrared and visible band.

Dust storm is most dominant factor to the radio wave attenuation. Large Martian dust storm can cause at least 3 dB or higher loss to Ka band wave. For a normal dust storm, the attenuation is about 1 dB. The attenuation much depends on dust mass loading, dust size distribution, etc. Most large dust storm occur in the southern hemisphere during later spring and early summer when the southern hemisphere become suddenly hot.